The ATLAS Tracker Upgrade:
Short Strip Detectors for the SLHC

Urmila Soldevila on behalf of the ATLAS SCT Collaboration
7 October 2009

11th ICATPP Conference on Astroparticle, Space Physics, Detectors and Medical Physics Applications
Villa Olmo (Como, Italia) 5-9 October 2009

Outline

- **LHC vs. SLHC**
- **Inner Detector (ID)**
- **Upgrades to the ATLAS Inner Detector**
- **Upgrade ID Layout**
- **Radiation Hard Technologies: n-on-p**
  - Miniature sensors:
    - Charge Collection under neutron and proton irradiation
    - Full Depletion Voltage
  - Full size prototypes sensors:
    - Electrical Characterization
- **Module Integration Concepts**
  - Barrel Stave
  - End-Cap Stave (Petal)
  - Super-Module
- **Conclusions**

LHC vs. SLHC

LHC

- Designed for luminosity of 10^{34} $cm^{-2}s^{-1}$
- In the first 5 years 700 fb^{-1} integrated luminosity
- First Colliding beams in November 2009

Super-LHC (SLHC)

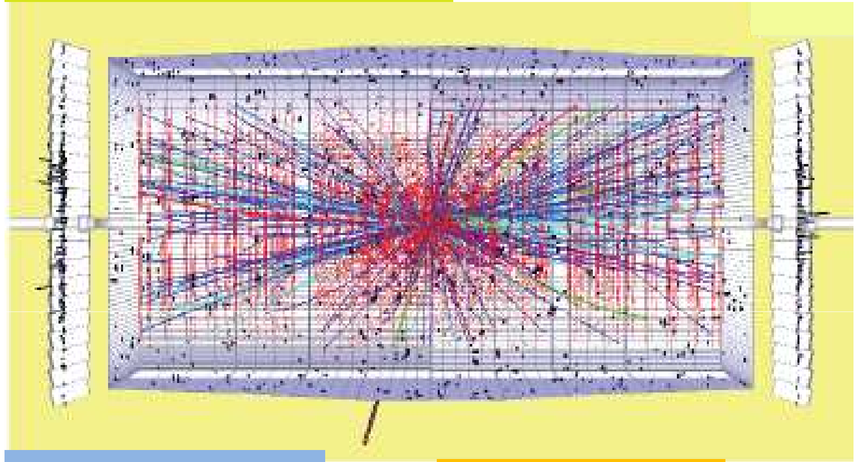
- Designed for luminosity of 10^{35} $cm^{-2}s^{-1}$
- SLHC Upgrade plans envision 3000 fb^{-1} (5 years)
- Starting around 2018-2020

Inner Detector (ID)

<u>Inner Detector</u> → Vertex (pixel) + Tracker (Silicon Strips, TRT)

High Occupancy :

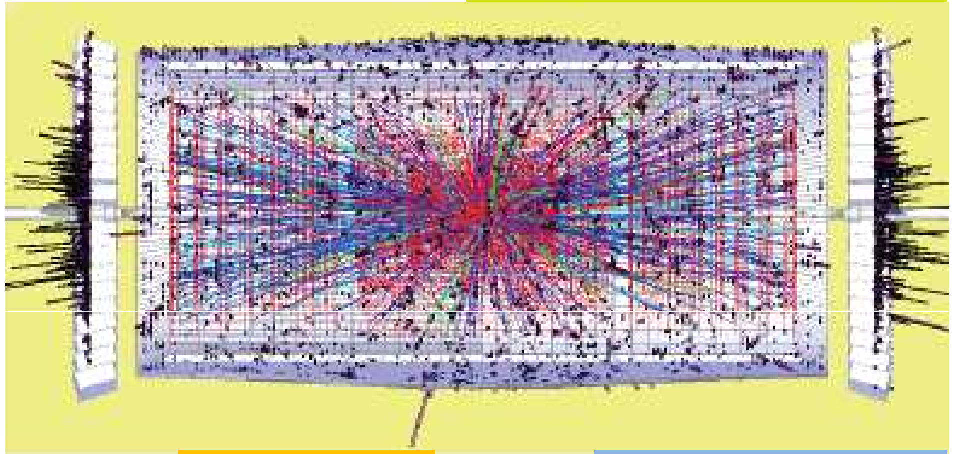
20 collisions per beam crossing **LHC**



700 track multiplicity

$L = 10^{34}\ cm^{-2}\ s^{-1}$ → $L = 10^{35}\ cm^{-2}\ s^{-1}$

SLHC 400 collisions per beam crossing



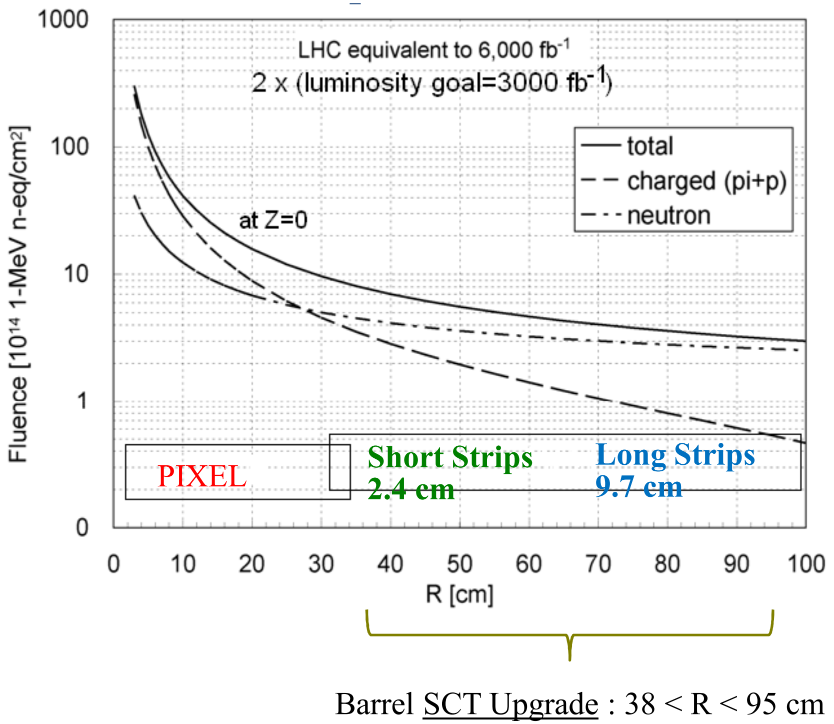
1400 track multiplicity

- TRT unable to cope with SLHC occupancy → All Silicon ID
- Finer granularity for the detectors to keep the occupancy at the same level of LHC
- This supposes for services:
  - x5 number of channels (for SCT)
  - In the same space !!

Inner Detector (ID)

Particle Fluence :

ATLAS Radiation Taskforce http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS /RADIATION/RadiationTF_document.html



- Neutrons > 50% at R $\geq$ 25 cm
- Strip detector damage largely due to neutrons

Designed fluences for sensors:

- B-layer at 3.7 cm: 2.2×10^{16} 1Mev n-equivalent/cm^2
- Outer pixel layers: 3×10^{15} 1Mev n-equivalent/cm^2
- Middle strip layer at 38 cm: 10^{15} 1Mev n-equivalent/cm^2
- Outer strip layer at 95 cm: 4×10^{14} 1Mev n-equivalent/cm^2

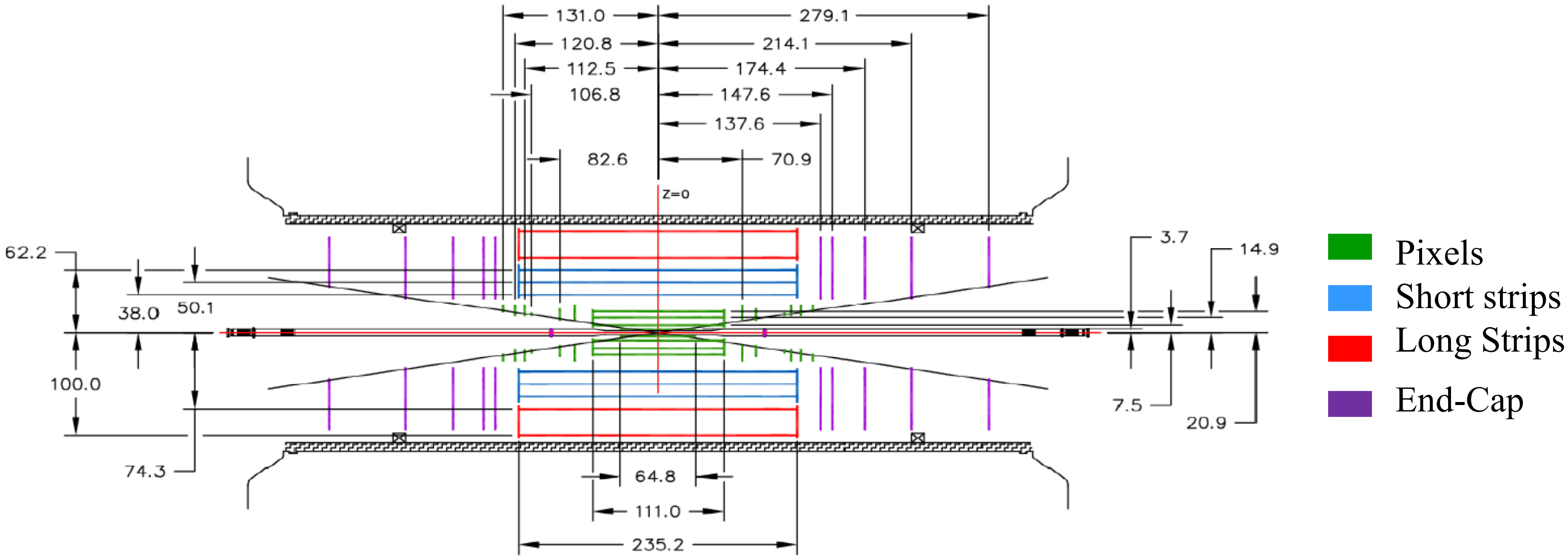
- This implies higher radiation hardness for sensors
- The ID will be replaced and technologically improved → R&D in RD50

Upgrades to the ATLAS Inner Detector

- New Detector Layout: Only silicon pixel and strips.
- Radiation hard technologies: n-on-p silicon strips.
- New Module Integration Concepts (low material budget).
- New Powering schemes (serial powering or DC-DC) to reduce the number of cables.
- Improved cooling system to maintain silicon temperature below -20^{o}C (CO_2 or C_3F_8) .
- Installation: Limited access time inside the cavern.

Urmila Soldevila (IFIC, Valencia)

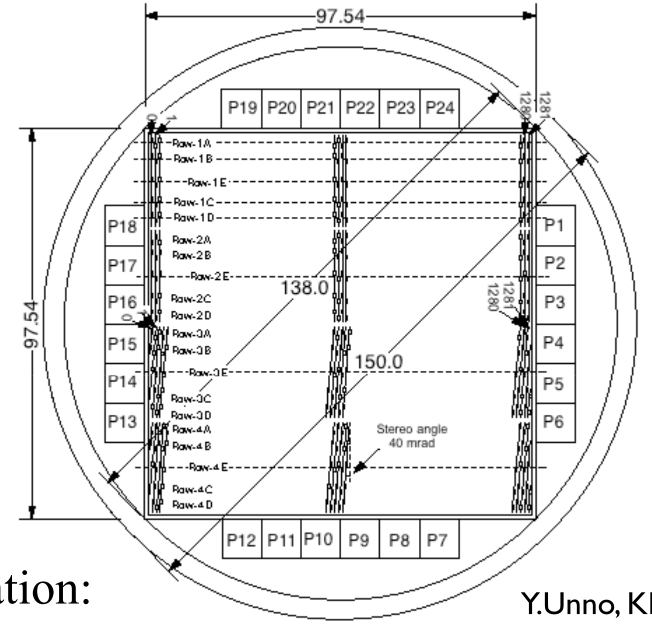
Upgrade ID Layout



- **Pixels:** considered options → 3-D or diamond detectors for innermost layer and n-on-p or n-on-n detectors for 3 outer layers
- **Strips**: 5 barrel layers: @ 38, 49, 60, 75, and 95 cm
  - 3 inner layers: SHORT STRIP LAYERS (24 mm-long strips)
  - 2 outer layers: LONG STRIP LAYERS (96 mm-long strips)
  - 5 double sided disks on each End-Cap
  - **The 3 outer layers + the end-caps will replace the TRT**
  - The design is expected to keep the occupancy below 1.6% at the innermost radius.

Radiation Hard Technologies: n-on-p

- p-bulk strip sensors (HPK ATLAS07) are investigated for the ATLAS ID upgrade. Their performance has been evaluated in terms of radiation damage on bulk.
  - 6 inch (150 mm) wafers
    - FZ1<100>(~6.7k Ωcm)
    - FZ2<100>(~6.2k Ωcm)
  - P-stop and p-stop+p-spray isolation
  - pitch 74.5 µm, thickness 320 µm
  - Miniature sensors (1cm x 1cm, 128 strips) →For irradiation studies
  - Full size prototype sensors (9.75 cm x 9.75 cm, 1280 strips)



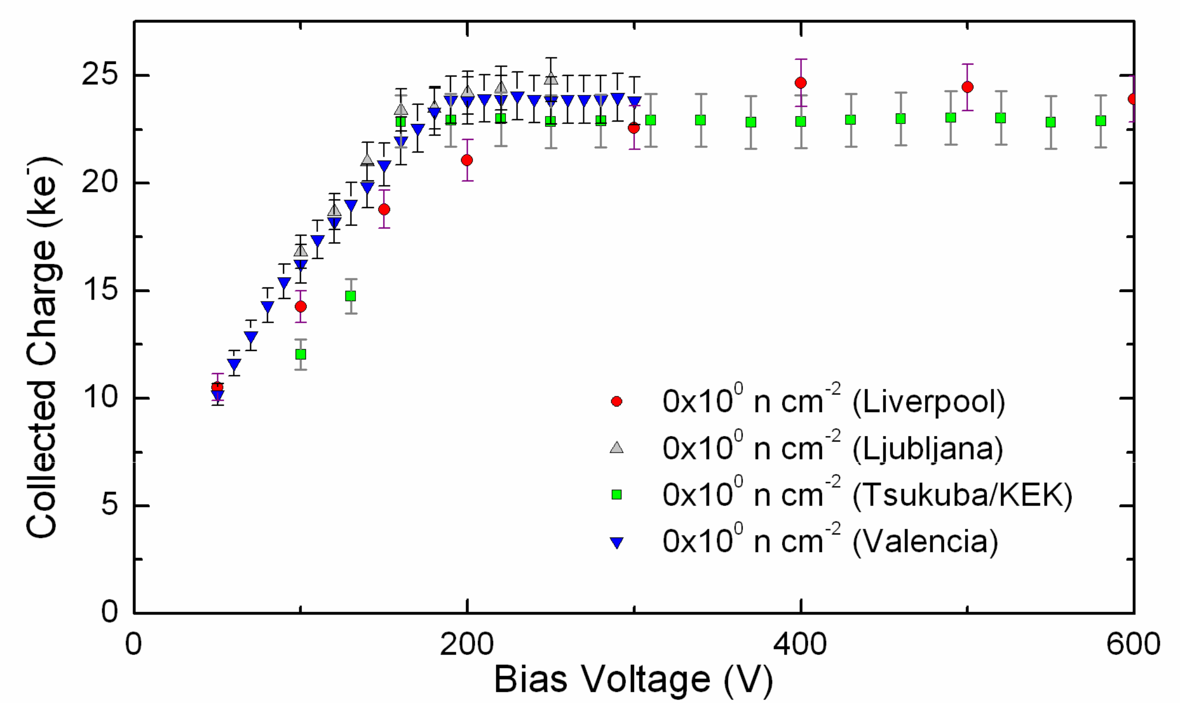
Y.Unno, KEK

Axial-Stereo Sensor

- The sensors are being developed by the R&D collaboration:

H. Chen, J. Kierstead, J.R. Carter, L.B.A. Hommels, D. Robinson, Univ. of Cambridge
Z. Li, D. Lynn, Brookhaven National Laboratory
K. Jakobs, M. Köhler, U. Parzefall, Physikalisches Institut, Univ. Freiburg
A. Clark, D. Ferrèrre, S. Gonzalez Sevilla, Univ. of Geneva
R. Bates, C. Buttar, L. Eklund, V. O'Shea, Dep. of Physics and Astronomy, Univ. of Glasgow
Y. Unno, S. Terada, Y. Ikegami, T. Kohriki, Institute of Particle and Nuclear Study, KEK
A. Chilingarov, H. Fox, Physics Dep., Lancaster University
A. Affolder, P. P. Allport, H. Brown ,G. Casse, A. Greenall, M. Wormald, Oliver Lodge Lab, Univ. of Liverpool
V. Cindro, G. Kramberger, I. Mandić, M. Mikuž, Jožef Stefan Institute and Dep. of Physics, Univ. of Ljubljana
I. Gorelov, M. Hoeferkamp, J. Metcalfe, S. Seidel, K. Toms, Dep. of Physics and Astronomy, Univ. of New Mexico
Z. Dolezal, P. Kodys, Faculty of Mathematics and Physics, Charles Univ. in Prague.
J.Bohm, M.Mikestikova, Academy of Sciences of the Czech Republic
C. Betancourt, N. Dawson, V. Fadeyev, M. Gerling, A. A. Grillo,
S. Lindgren, P. Maddock, F. Martinez-McKinney, H. F.-W. Sadrozinski,
S. Sattari, A. Seiden, J. Von Wilpert, J. Wright, SCIPP, UC Santa Cruz
R. French, S. Paganis, D. Tsionou, Dep. of Physics and Astronomy, The Univ. of Sheffield
B. DeWilde, R. Maunu, D. Puldon, R. McCarthy, D. Schamberger, Dep. of Physics and Astronomy, Stony Brook Univ.
K. Hara, N. Hamasaki, H. Hatano, S. Mitsui, M. Yamada, School of Pure and Applied Sciences, Univ. of Tsukuba
C. García, C. Lacasta, S. Martí i Garcia, M. Miñano, U.Soldevila IFIC (Centro Mixto CSIC-UVEG)

Miniature Sensors: Charge Collection



Pre-Irradiation

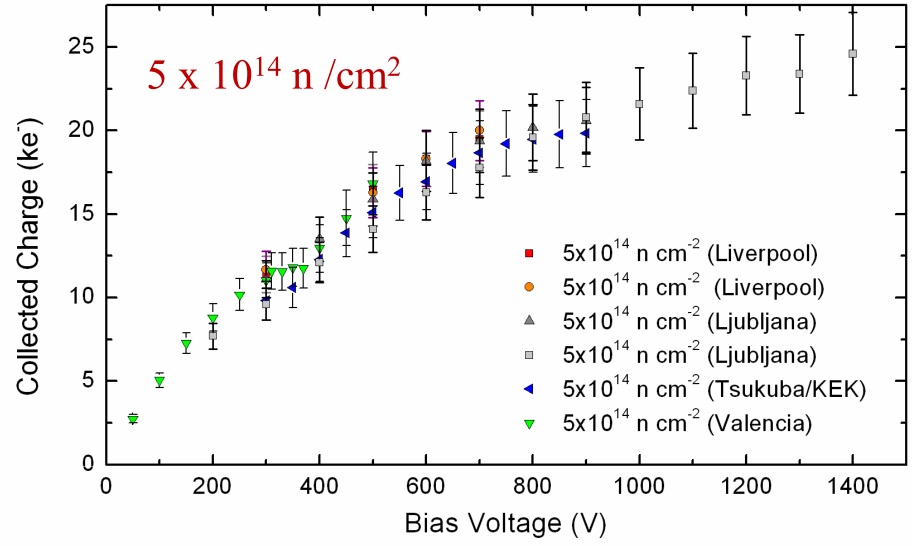
Good agreement between sites/systems. Systematic differences under control.

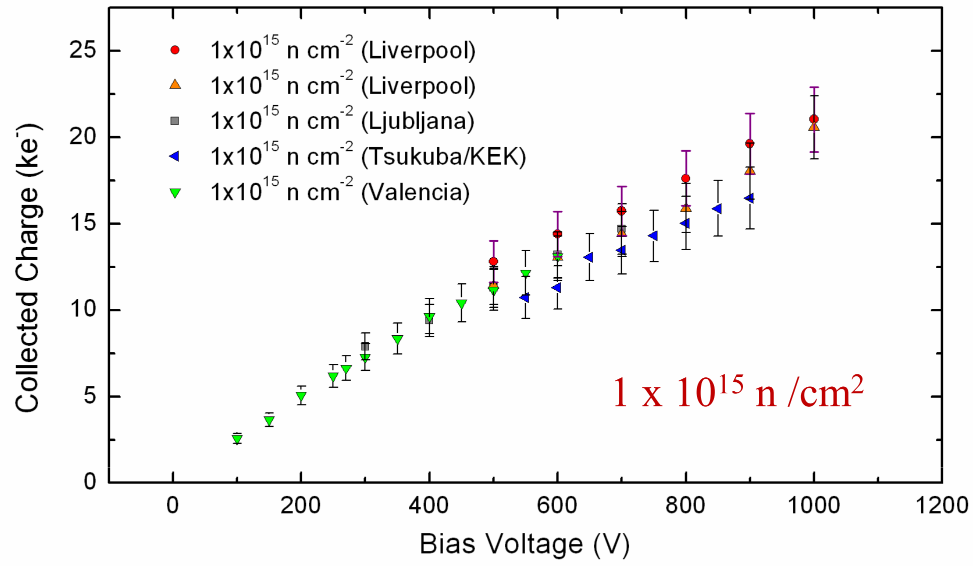
ATLAS institutes involved :

- **Valencia** uses Beetle based system (MPV charge, analogue data, 25ns shaping time)
- **Ljubljana** and **Liverpool** use SCT128A based system (MPV charge, analogue data, 25ns shaping time)
- **Tsukuba/KEK** uses a CAMAC 4-ch system with discrete amps (MPV charge, analogue data, 20ns PT)
- **UC-Santa Cruz** uses PTSM based system (Median charge, binary data, 100 ns shaping time)

Radiation Hard Technologies: n-on-p

Miniature Sensors: Neutron Irradiation



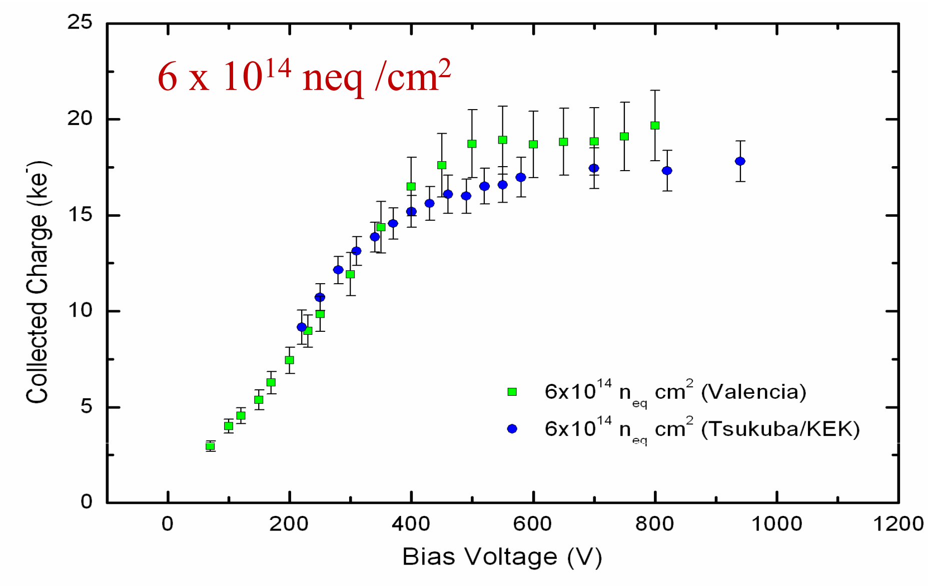


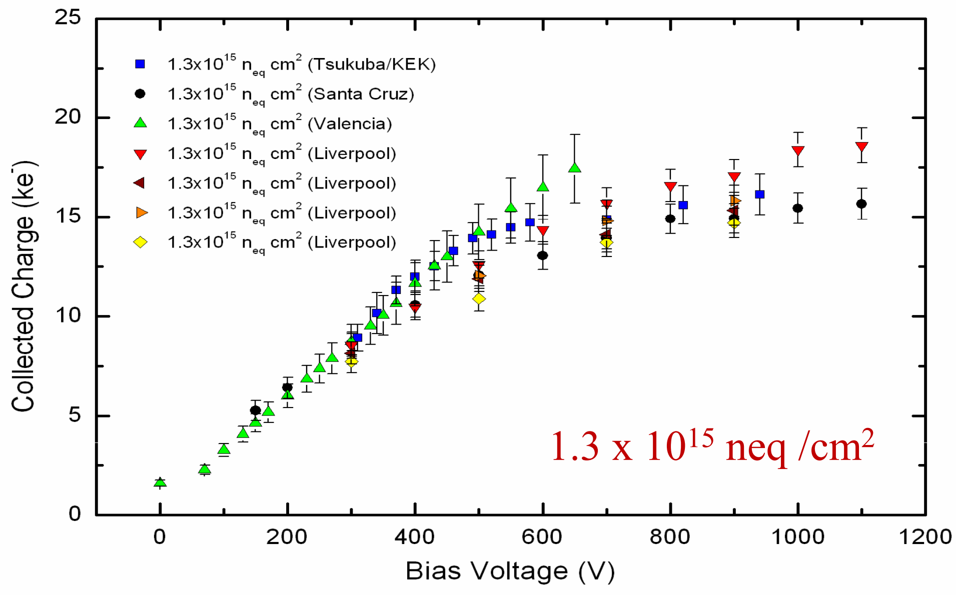
- Ljubljana and Tsukuba/KEK annealed for 80 minutes at 60ºC → CCE increases by ~25%+/-10%
- Liverpool and Valencia do not anneal (with annealing correction i.e. CCE reduced by -20%+/-10%)

@500V	CC	Expected noise	S/N achievable
@ 5x10^{14} n/cm^2	14-16 Ke-	950e-	~16
@ 1x10^{15} n/cm^2	11-13 Ke-	600e-	~20

Good!

Miniature Sensors: Proton Irradiation



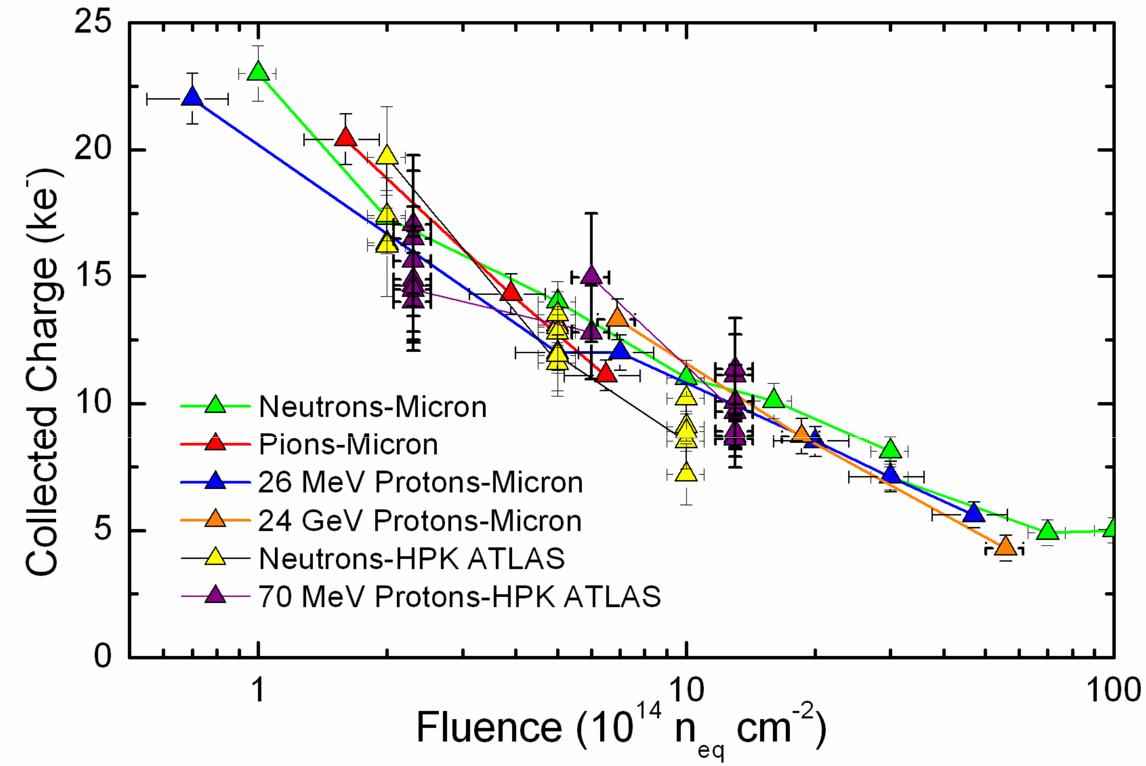


- Ljubljana and Tsukuba/KEK annealed for 80 minutes at 60ºC → CCE increases by ~25%+/-10%
- Liverpool and Valencia do not anneal (with annealing correction i.e. CCE reduced by -20%+/-10%)

@500V	CC	Expected noise	S/N achievable
@ $5\text{x}10^{14}$ n/cm^2	16-19 Ke-	950e-	~18
@ $1\text{x}10^{15}$ n/cm^2	11-14 Ke-	600e-	~20

Good!

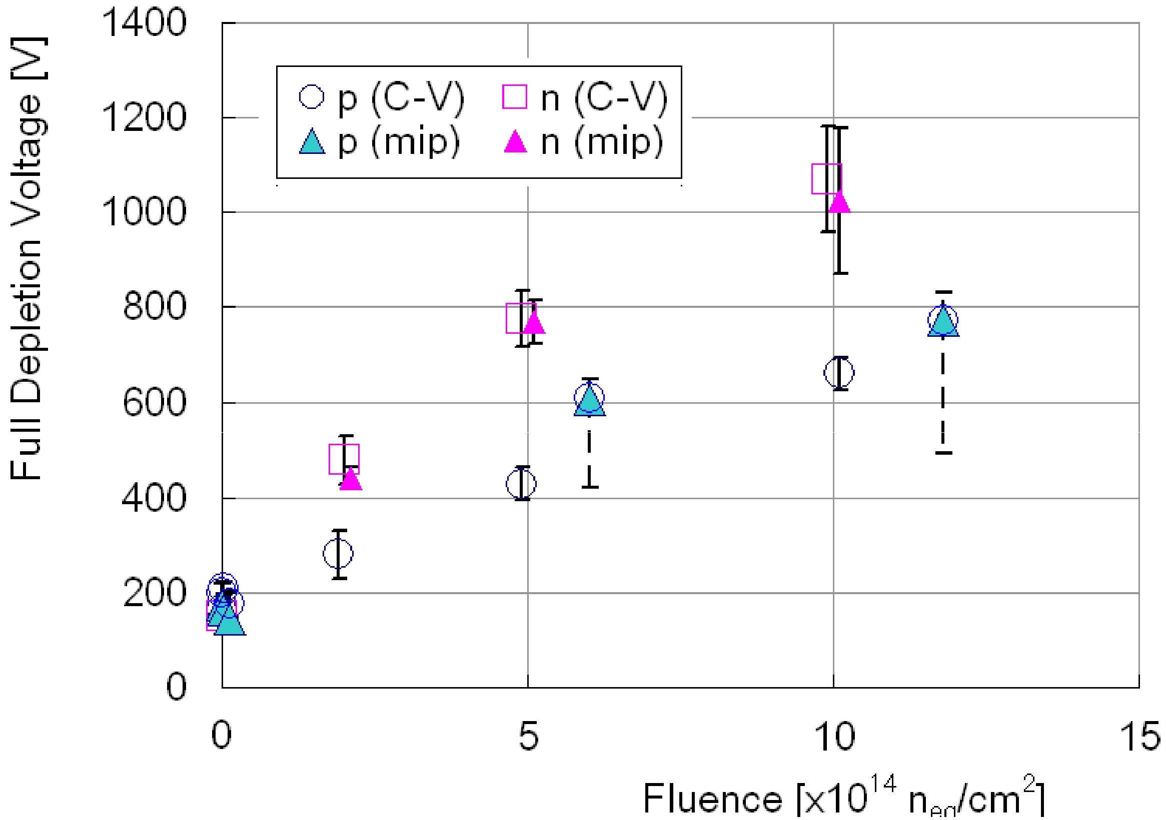
Miniature Sensors: N-on-P FZ Irradiations (HPK and Micron sensors)



Micron data from A. Affolder, P.P. Allport & G. Casse, to be published in the proceedings of TIPP09.

- Performance of n-on-p FZ sensors produced at Micron and Hamamatsu are the same after all measured irradiation sources. HPK data shown from all sites. Pion irradiation measurements corrected for annealing during run.

Miniature Sensors: Full Depletion Voltage Evaluation



Series Sensors FZ1

- Protons:
  FDV~700V @10^{15} cm^{-2}
- Neutrons:
  FDV~800V
  @ 5 x 10^{14} cm^{-2}

↓

operation in partial depletion is foreseen

K. Hara et al., "Testing of bulk radiation damage of n-in-p silicon sensor for very high radiation environment" , 7th International "Hiroshima" Symposium on the Development and Applications of Semiconductor Tracking Detectors.

Full Size Prototype Sensors: Electrical Characterization

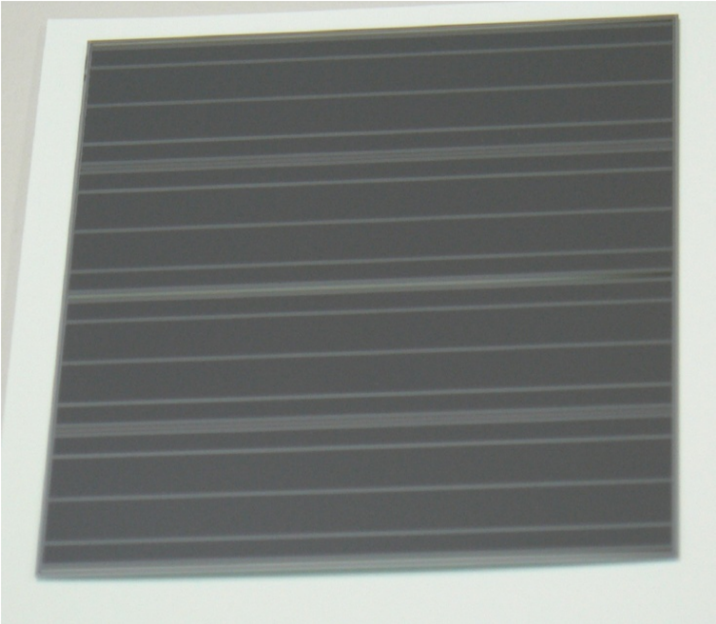
ATLAS institutes involved:

- University of Cambridge → 2 sensors: W15, W16
- Stony Brook University → 9 sensors: W19, W21-23, W25-29
- Inst. of Physics and Charles Univ, Prague → 6 sensors: W32, W33, W35, W37, W38, W39
- University of Geneva → 2 sensors: W17, W18

Total number of tested sensors: **19**

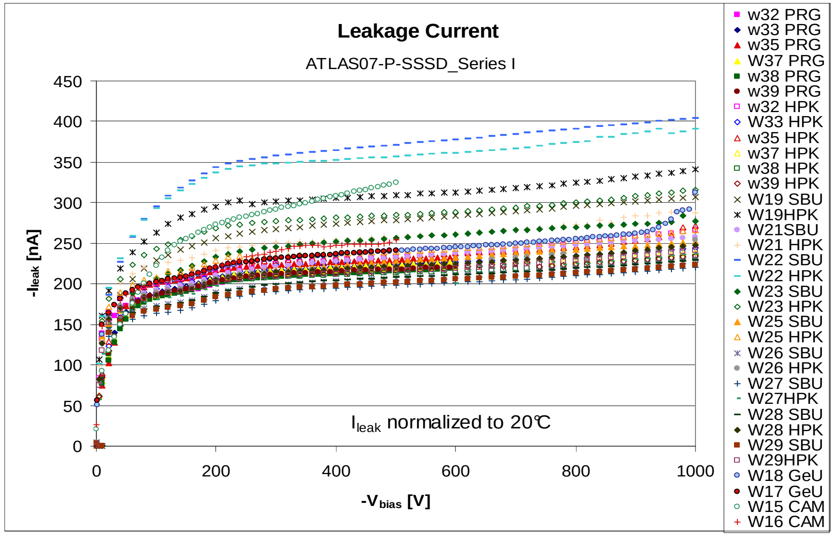
ATLAS07 Full Size Sensors

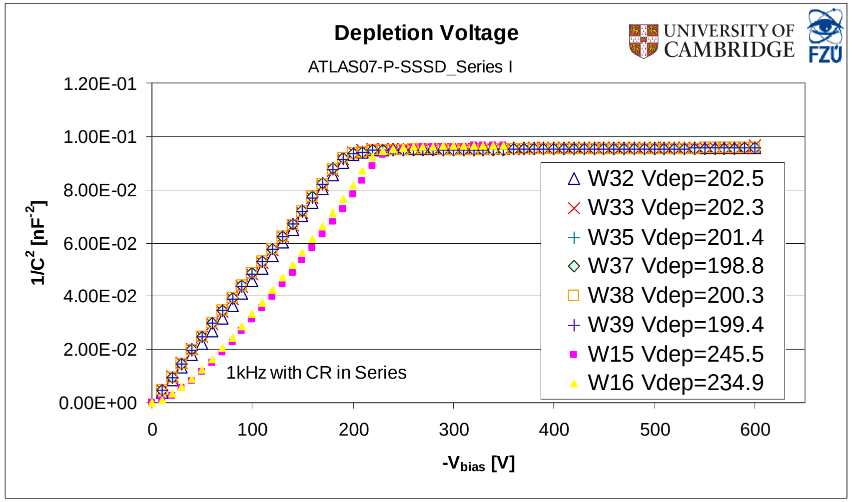
- 9.75 cm x 9.75 cm
- 4 segments:
  - two with "axial" strips. 74.5 μm pitch
  - two with "stereo" strips. 74.4 μm pitch, 40mrad



Radiation Hard Technologies: n-on-p

Full Size Prototype Sensors: Bias Scan

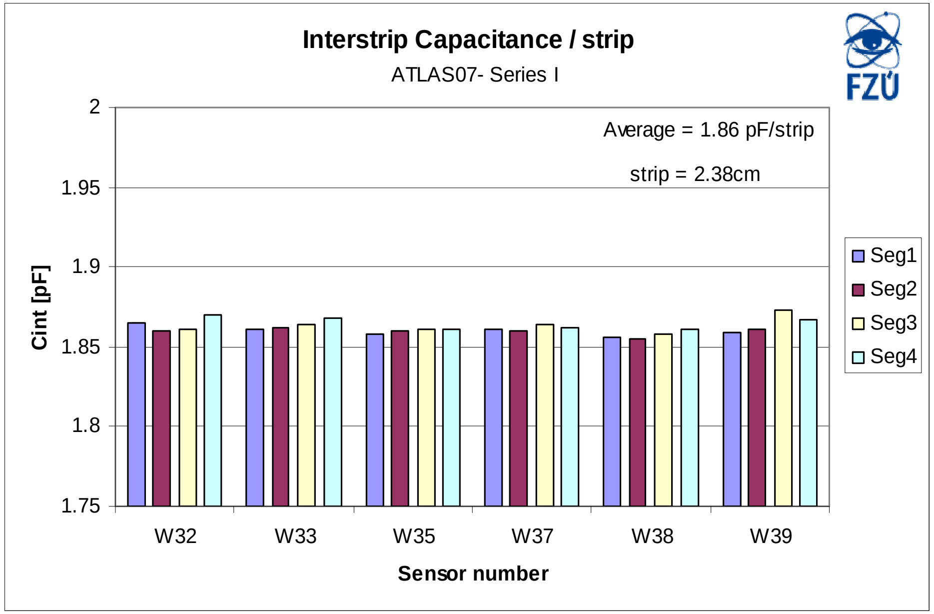




- No microdischarges with exception one sensor (Vbd~420V).
- Sensors satisfy the ATLAS07 Technical Specification (<200um @ 600V)
- IV scan was repeated after bias scan and strip scan.
- Current was usually higher by 10%- 20% and breakdown for 2 sensors at ~380V.

- Estimated values of Vdep:
  - 6 sensors (Prague) 199-203V
  - 2 sensors (Cambridge) 235-245V
- All tested sensors satisfy specifications: Vdep < 500V

Full Size Prototype Sensors: Bias Scan



All tested sensors:

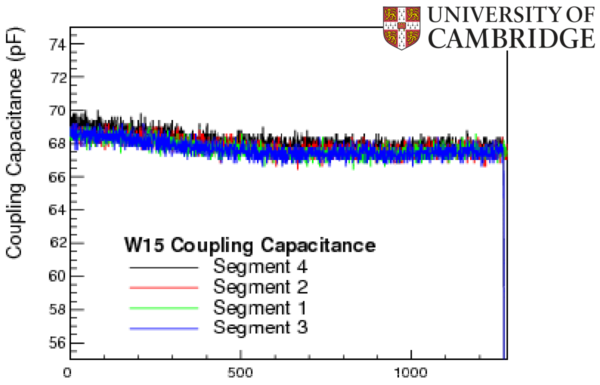
Cint ~ 0.75-0.80 pF/cm
< 1.1 pF/cm (ATLAS specification)

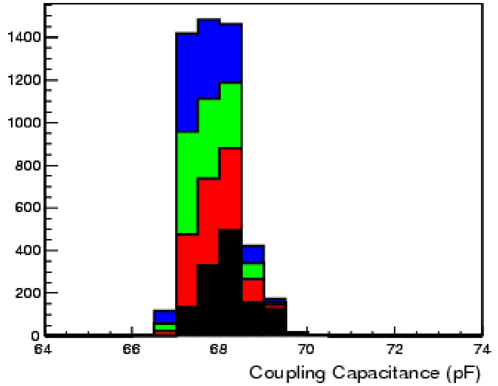
Cint/strip = 1.86pF/strip

- Measurements taken on central strip with either neighbour grounded. Including next-to-neighbours results in 10-15% higher readings.

Full Size Prototype Sensors: Strip Scan

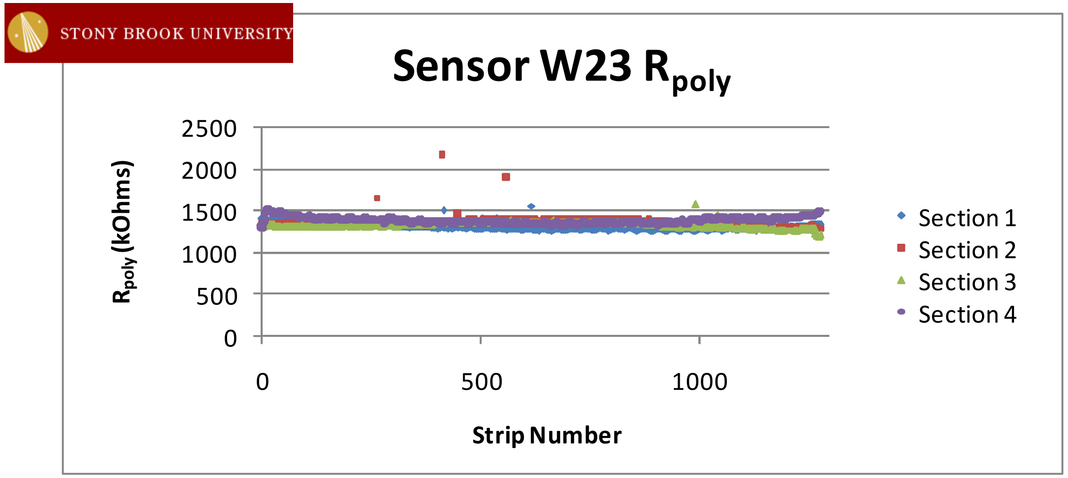
For 5 sensors





Ccpl = 66-68pF/strip

ATLAS07 Specification:
Ccpl/strip>47.6pF
Strip length =2.38cm



Rbias=1.30MΩ -1.45MΩ

ATLAS07 Specification:
Rbias=1.5±0.5MΩ

Module Integration Concepts

Barrel Stave

➢ Hybrid glued to sensors. These glued to bus tape. This glued to cooling substrate.

60 cm, 9 cm strip, 4 chips wide

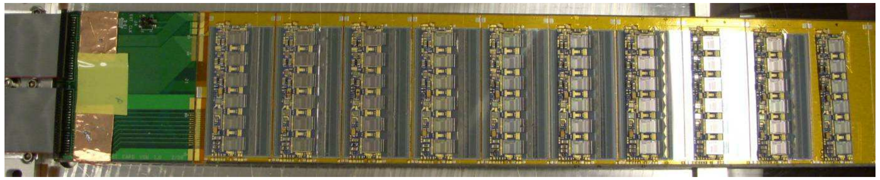
Stave-06

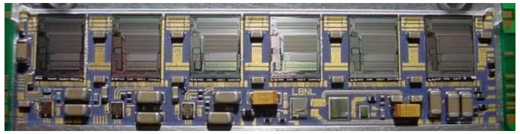
Results agree with ABCD performance

1 m, 3 cm strip, 6 chips wide

Strip Stave from LBNL

Stave-07

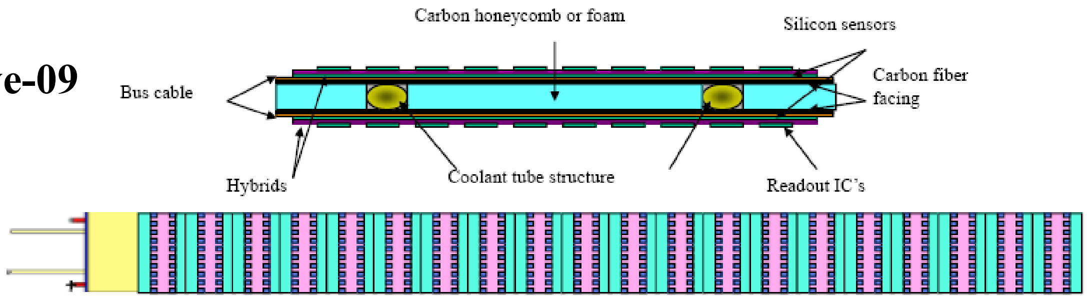




- Individual hybrids/modules work well electrically. Good noise performance. All are 900e-
- Tested 6 module on stave with ABCD chips. Serial Powering lines.
- Working ongoing

Under Construction: 1.2 m, 2.5 cm strip, 10 chips wide (20 chips/hybrid)

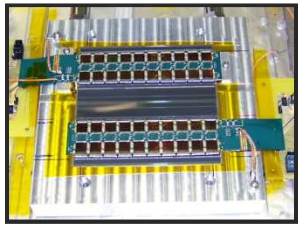
Stave-09



- P-type sensors
- ABCN25 chips
- Kapton Hybrid
- Embedded Bus Cable
- Stave mechanical core

C.Haber (LBL)

1st prototype module from Liverpool



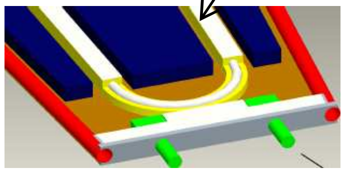
Module Integration Concepts

Petal

➢ Follows quite closely the barrel stave concept

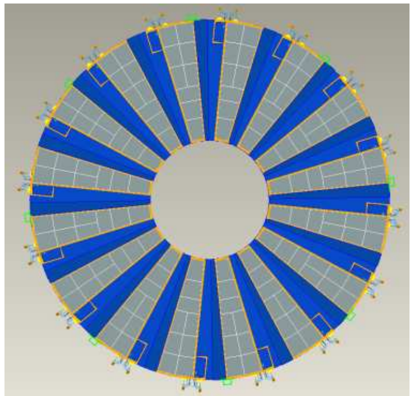
C.Lacasta (IFIC,Valencia)

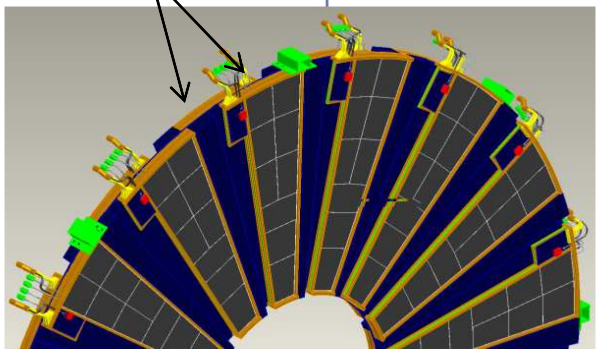
- 2 carbon facings + Honeycomb sandwich core
- Independent e-services + Bus Cable
- Independent C02 cooling pipe



- petal surface: 830 cm^2
- 5 disks on each end-cap
- 32 petals/disk (16 on each side)
- 6 different detector types mounted on petal
- 9 different hybrid types
- 116 chips/petal

Double sided

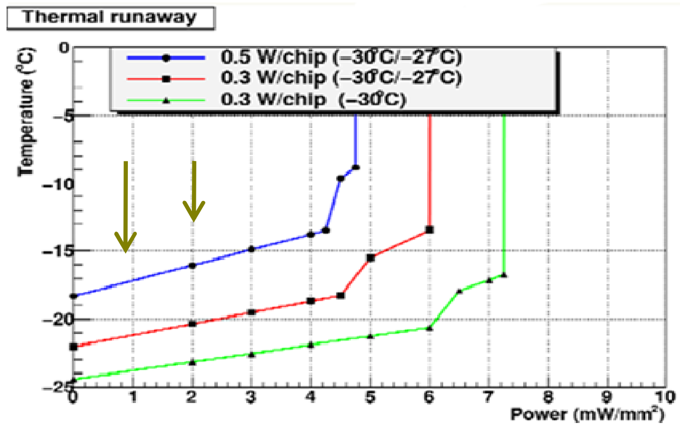


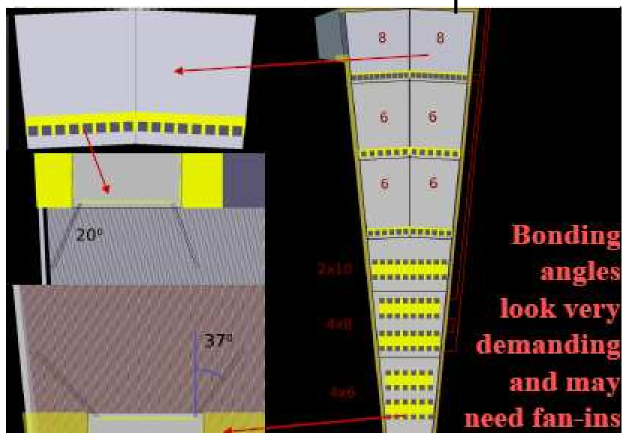


Simulations of a disk. Issues: Layout, modularity, powering

Thermal simulations to explore the behaviour at critical points:

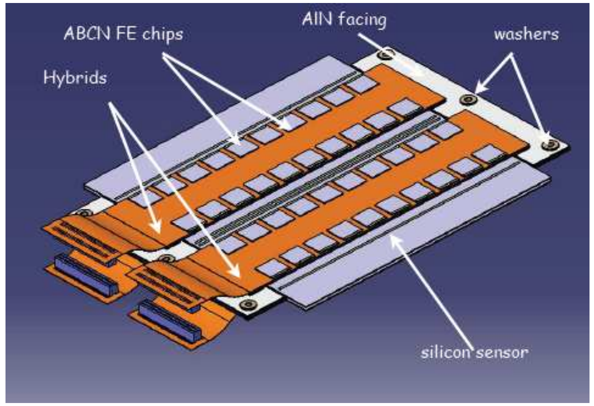
- Assumed -30ºC coolant temperature (-27ºC on the return pipe)
- The simulation results show that the temperature on sensors is within safety range (to be confirmed with prototypes) .





Module Integration Concepts

Super-Module



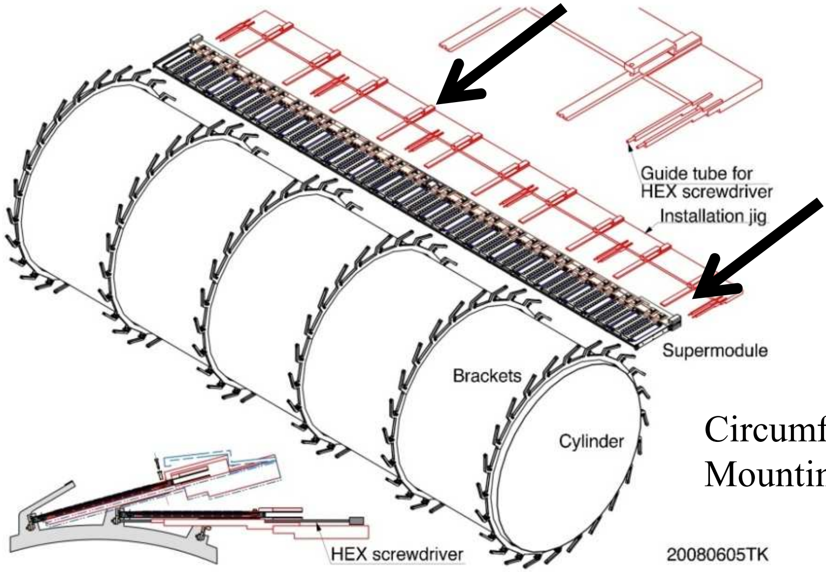
1) Build individual modules :

- Double sided module
- 2 silicon (short) microstrip sensors: n+-on-p, 10x10 cm^2
- 4 bridged hybrids with ABCN asics each

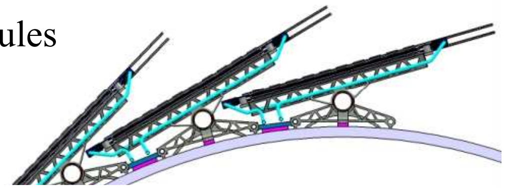
2) Insert modules into a frame: Super-module **(Based on SCT experience)**

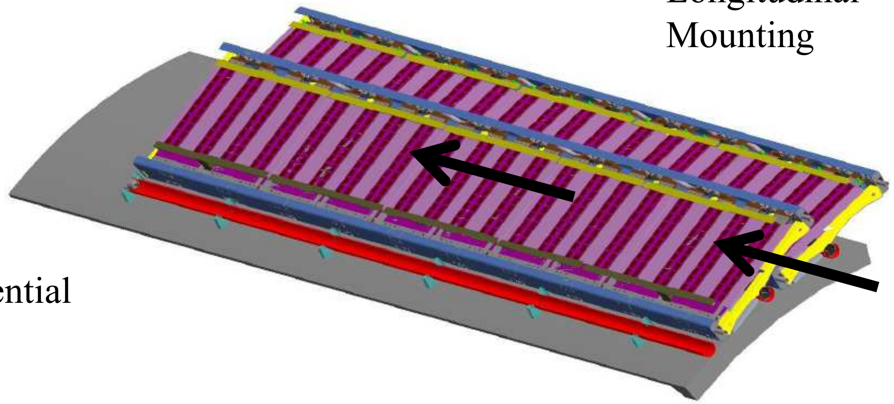
2 proposals for module integration into cylinders:

- Lateral insertion (KEK): Installation of the Super-Modules, cylinder by cylinder
- End-insertion (Geneva): Barrel structures can be assembled before the Super-Modules are integrated.



Circumferential Mounting





Longitudinal Mounting

Conclusions

- The tracker of ATLAS will have to be replaced for the LHC upgrade.
- Lots of **R&D** has already been carried out and ideas are near to converge.
- **Strip community** are investigating the short (2.4cm) and the long strips (9.6 cm) sensors for barrel and EC with stave or petal concept.
- Miniature and Full Size p-type sensors have been manufactured by Hamamatsu (HPK):
  - Good performance in terms of charge collection efficiency under neutron and proton irradiation. S/N of ~20 (16) should be achievable with short (long) strip detector.
  - Sensors will operate at partial depletion → p-bulk sensor good candidate.
  - All tested full size sensors satisfy ATLAS07 Technical Specification for leakage current, full depletion voltages, Cint measured in the bias voltage scan.
  - Strip scan was performed on 5 full size sensors. Ccoupling and Rbias were uniform across the whole sensor and within specifications.
- Prototyping for Module Integration is progressing.
- Good progress but important decisions to take.

- Thank you -

- Backup -

- Services:
  - The required high granularity supposes (in the same space)
    - x5 number of channels
    - x5 number of cables

↓

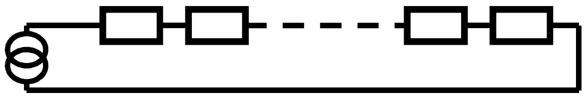
New options in powering (not individual powering)

Current ID	Area (m^2)	Channels	Upgrade	Area (m^2)	Channels
Pixels	1.8	80M	**Pixels**	5	~300M
SCT	61	~6.3M	**Short Strips**	60	~30M
TRT		400K	**Long Strips**	100	~15M

Backup

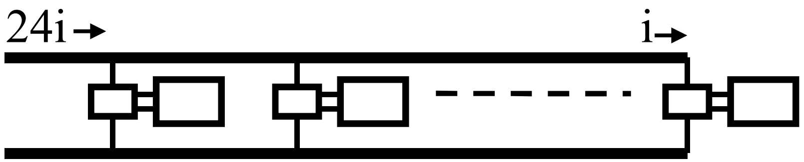
- Several options on powering: DC/DC or serial.
  - Cannot have individual module powering → too much material and no space.
  - Requirements: High power efficiency, low noise, safety (overcurrent, overvoltage, overtemperature).

Serial Powering



Serial Powering scheme has been shown to perform well on 6 and 30 module staves (Stave06,Stave07)
- Excellent noise performances
- Current issues:
  - Protection schemes (shunt regulators) possible integration into FE chips
  - Custom current source

DC-DC Powering

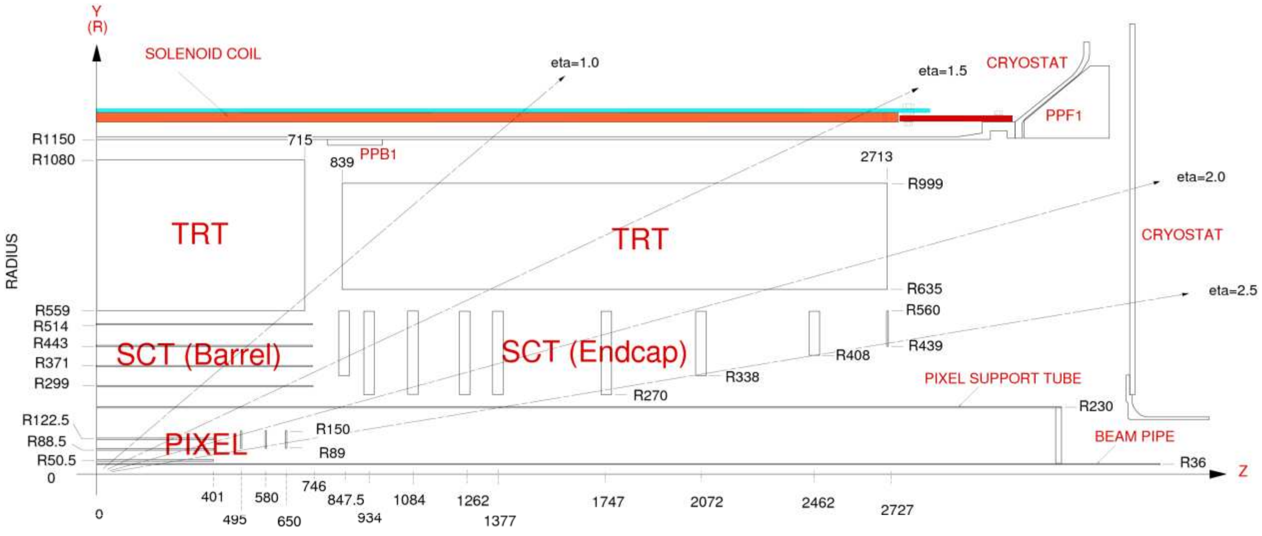


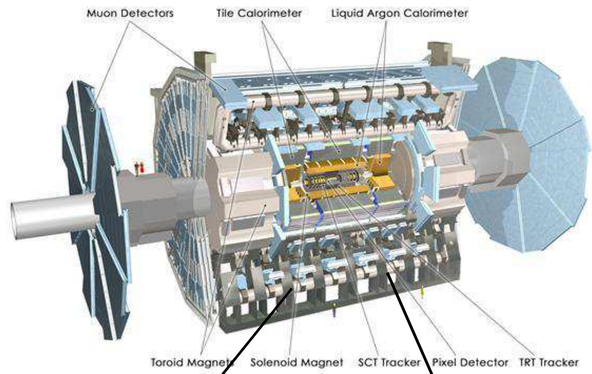
DC/DC scheme:
- Only 1 power line/stave (10-12V)
- Distribution with 2 conversion stages:
  - Stage 1 → 2converters: 2.5V analog and 1.8V digital
  - Stage 2 → On-chip switched capacitor
- High granularity of the power distribution
- Very flexible

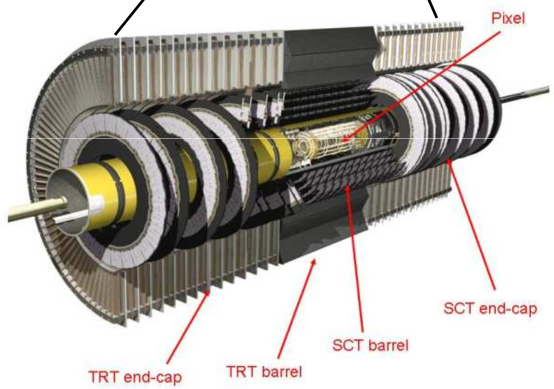
Currently anticipated evolution of the ATLAS upgrade (http://atlas.web.cern.ch/Atlas/GROUPS/UPGRADES/)

Milestone	Date
Straw Man & options fixed	Dec 2006
R&D towards inner detector conceptual design	2007-2010
LoI	May 2010
Technical Proposal, Initial MoU and Costing	April 2012
Inner Tracker TDR	Dec 2013
Production readiness reviews and ramp up production	2014
New Insertable B-layer Installation	End 2014
Procure parts, Component assembly	2014 - 2016
Surface assembly	September 2016 - end 2017
Surface testing	2018
Stop LHC	Sep 2018
Remove old detectors, install new	Oct 2018 - Dec 2019
Commission new detectors	Jan 2020 - Mar 2020
Take data	April 2020

Current Inner Detector



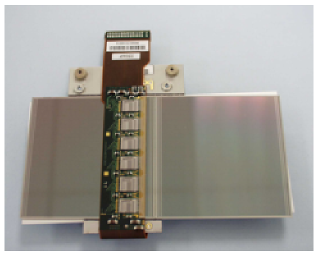


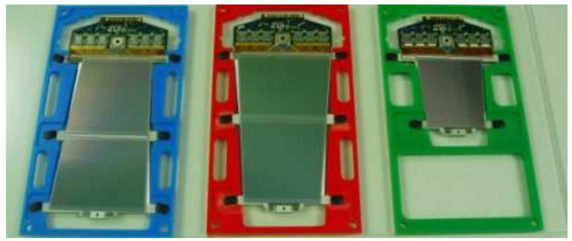


Pixels (n+-on-n sensor technology**):** 3 barrels + 2x3 discs (5 < R < 15cm)
Strips (SCT) (p+-on-n sensor technology)**:** 4 barrels + 2x9 discs (30 < R < 51cm)
TRT: Barrel + Wheels (4mm diameter straw drift tubes) (55 < R < 105cm)

Designed fluences for sensors:
- Pixel layer 0: 1 x 10^{15} 1MeV n-equivalent /cm^2
- SCT Barrel layer 1: 8 x 10^{14} 1MeV n-equivalent /cm^2
- SCT End-cap disc 9: 7 x 10^{14} 1MeV n-equivalent /cm^2
- TRT outer radius: 3 x 10^{13} 1MeV n-equivalent /cm^2

SCT Module (Barrel & Endcaps)Designs



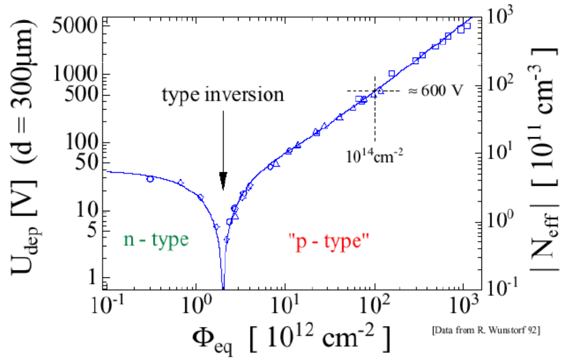


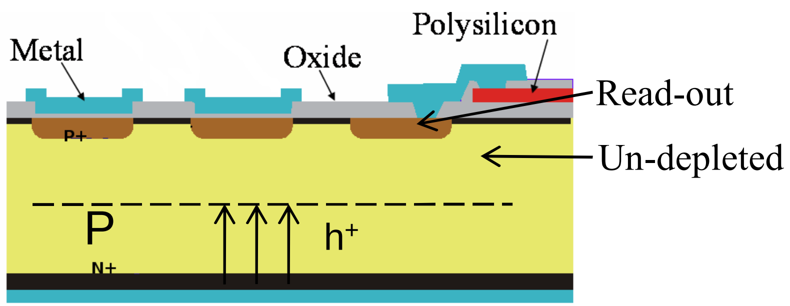
p-type Detectors: Motivation

The current SCT sensors use **p-on-n** technology. They are not sufficient radiation hard for the LHC upgrade.

P-on-N

- Holes collected
- Type inversion
  - Deposited charge can not reach electrode in the corresponding collection time





N-on-N

- Electron collected
  - Higher mobility
  - Longer trapping time
- Type inversion
  - Deposited charge can reach the electrode
  - It can work under-depleted
- Doubled-sided processing
  - Most expensive
  - Limited suppliers

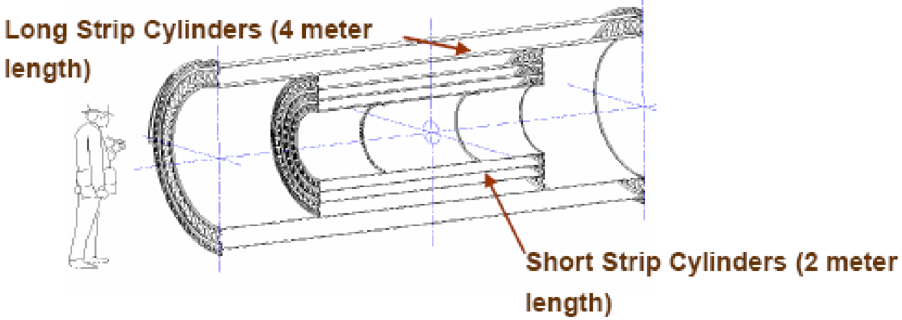
N-on-P

- Electron collected → Higher mobility
- No type inversion
  - It can work under-depleted
- Single-sided processing
  - ~50% less expensive than n-on-n
  - More suppliers
- Maybe as radiation hard as n-on-n

Current SCT Detector

Strips Detector in numbers

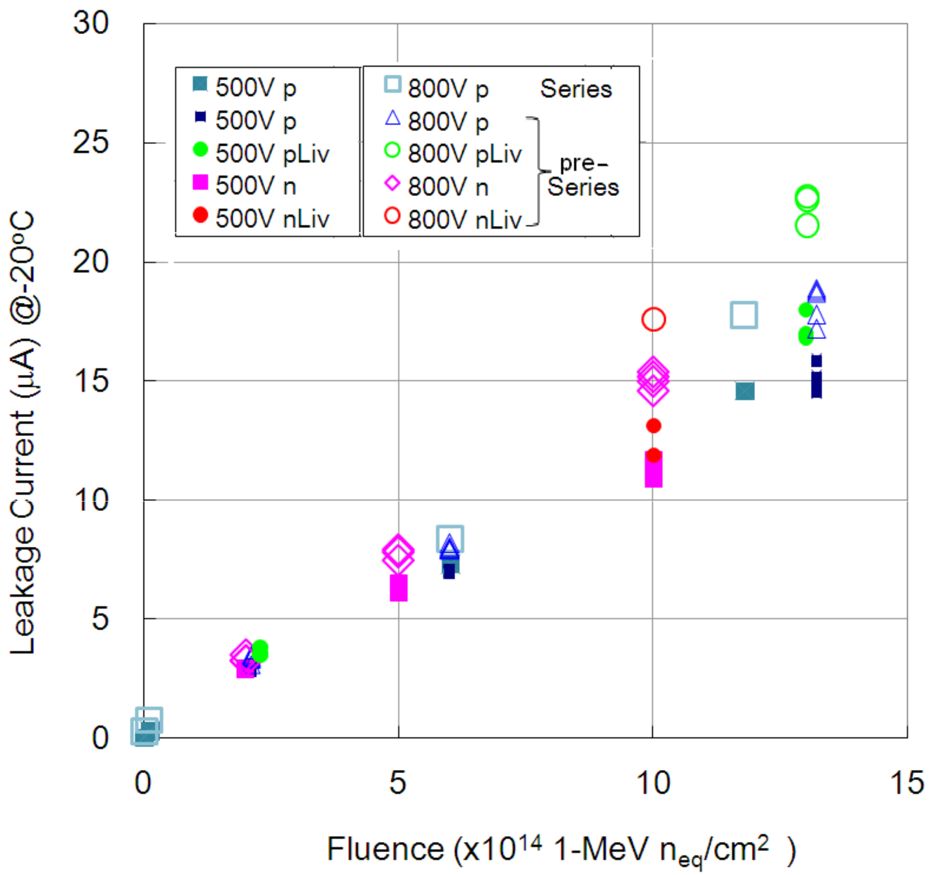
	Layer	Type	Radius [cm]	Phi segmentation	Number of modules per half single sided stave	Number of 128-ch FEIC per half single sided stave
Barrel	0	Short Strips	38	28	10	400
	1	Short Strips	49	36	10	400
	2	Short Strips	60	44	10	400
	3	Long Strips	75	56	19	190
	4	Long Strips	95	72	19	190
	Total number of staves for the Barrel					*236*
	Total number of modules for the Barrel					*14,336*
	Total number of FEIC for the Barrel					*270,080*
Endcap	*Total number of staves for one End-cap*					*1,152*
	Total number of 128-ch FEIC for the two End-cap					*57,088*
Total number of 128-channel FEICs						327,168
Total amount of channels						41,877,504



- *Current SCT detector*
  - *4088 modules*
  - *49k 128-channel FEIC*
  - *6.3M channels*

Philippe Farthouat (CERN)

Leakage Current (@500/800V) with protons



Current / V $= \alpha \cdot \phi$

V_{FD}~700V
$\phi = 10^{15}$ cm^{-2}

- The damage constant (slope) ~ consistent with n-bulk damage constant ($\alpha \sim 4 \times 10^{-17}$ A/cm)
- The leakage current of non-irradiated p-bulk sensors is at the similar level to HPK n-bulk sensors

Agreement between sites (Tsukuba/KEK and Liverpool)

- **proton/neutron damages contribute similarly to leakage current increase**

K. Hara et al., "Testing of bulk radiation damage of n-in-p silicon sensor for very high radiation environment" , 7th International "Hiroshima" Symposium on the Development and Applications of Semiconductor Tracking Detectors.